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Biological Control in the Canadian Forestry Service

by M. A. Hulme

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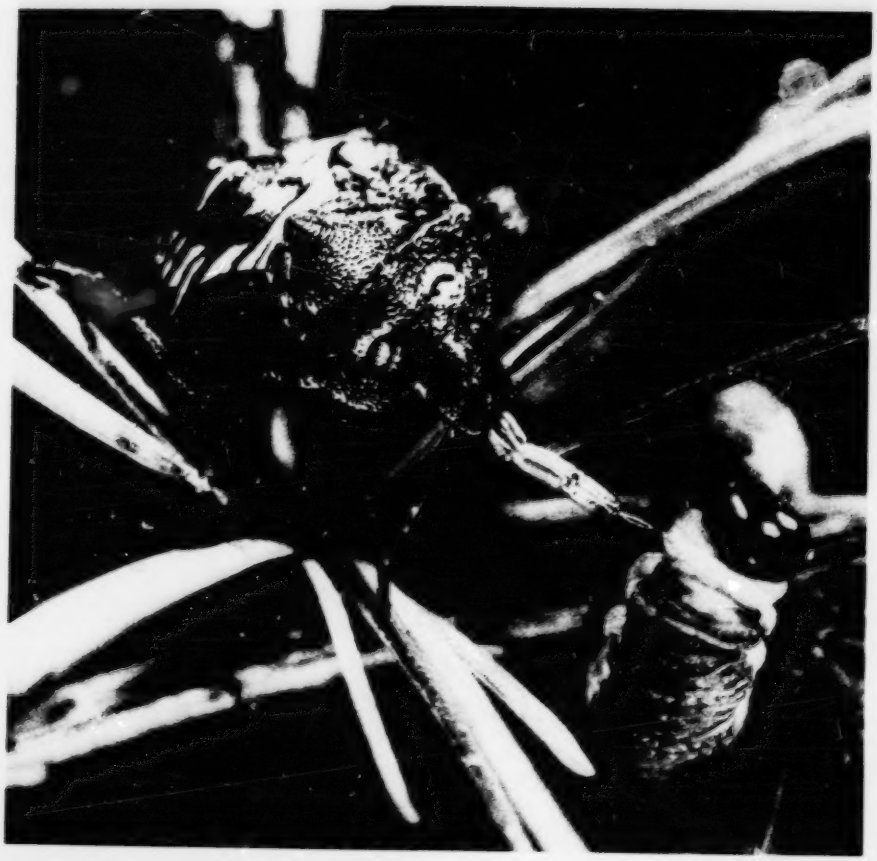

Cover Photo - Pentatomid predator feeding on a sawfly larva.

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FOREWORD

The following review of biological control research in the Canadian Forestry Service (CFS) was undertaken to define future plans for such research within CFS. The draft report has been extensively reviewed at all CFS laboratories, and the final report with its 43 recommendations was approved by the Committee of Establishment Directors. Responsibility for ensuring that the recommendations are implemented rests with the Director of Research and Development at Headquarters, who reports directly to the Director General of Research and Technical Services.

J.H. Cayford
Acting Director General
Research and Technical Services
June 30, 1982

ABBREVIATIONS

B.t.	- *Bacillus thuringiensis*
CANUSA	- Canada United States Spruce Budworms Program
CFS	- Canadian Forestry Service
CIBC	- Commonwealth Institute of Biological Control
FIDS	- Forest Insect and Disease Survey
FPMI	- Forest Pest Management Institute
GLFRC	- Great Lakes Forest Research Centre
LFRC	- Laurentian Forest Research Centre
MFRC	- Maritimes Forest Research Centre
NeFRC	- Newfoundland Forest Research Centre
NoFRC	- Northern Forest Research Centre
PFRC	- Pacific Forest Research Centre
PNFI	- Petawawa National Forestry Institute
PY	- Person Year or Years
USDA-FS	- United States Department of Agriculture - Forest Service

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SUMMARY

1. Biological control using living organisms is one of the five recognized approaches to forest pest management. The others involve quarantine, planting pest-resistant trees, silviculture, and use of chemical pesticides. In selecting a control there are three main questions. Does it work? What does it cost? Is it socially acceptable?

2. Chemicals have dominated control options and are thus the norm for comparison. While effective, they have limitations - control after each application is short-term, there may be several undesirable side effects, and social acceptability has been poor. Furthermore, as protection strategies change from merely keeping trees alive to maintaining incremental growth, more chemicals will be required.

3. Much interest has recently been shown by outside agencies in emphasizing biological control, especially in the context of integrated pest management, mainly to lower our degree of dependence on chemical insecticides. Biological control is slower than chemical control, its effects may be more difficult to monitor, and its mechanism of action can be complex. However, control can be virtually permanent when it is self-perpetuating. The notable success was the biological contol of the European spruce sawfly, a pest in the 1920s comparable to spruce budworm today.

4. There are few economic comparisons between chemical control and biological control. Where data are available, the benefit : cost ratio for biological contol is impressive.

5. Some outstanding research successes of CFS have been in biological control of such insects as larch sawfly, introduced pine sawfly, European spruce sawfly, satin moth, larch casebearer, winter moth, redheaded pine sawfly, European pine sawfly, Swaine jack pine sawfly, mountain-ash sawfly, white-marked tussock moth, Douglas-fir tussock moth, and European pine shoot moth. In some cases the controls are self-perpetuating but in others the control agents must be periodically reapplied. Success (probably limited by application problems) has been obtained against spruce budworm for short-term control. Forest tent caterpillar and other Lepidoptera (butterflies, moths) can also be controlled. Little success has been obtained against

bark beetles mainly because little has been attempted. Global successes with biological control are also highlighted in this report.

6. Only one-fifth of the CFS budget for forest protection research (FIDS excluded) is devoted to biological control with more than three-quarters of the effort on organisms causing diseases in insects – mainly viruses followed by bacteria, then fungi. Support is weak for control using predators and parasitic insects despite several past successes and the fact that costly and uncertain registration are not necessary. No attempts have been made to control pests by inundation release of parasitic insects, a technique successfully practiced in Russia and China.

7. CFS allots almost 50 PY for biological control research. More than 60% of these PY are concentrated on insect disease research at FPMI. The remaining PY, divided about equally among diseases and predators plus parasitic insects, are scattered across the country. Allocations are particularly low in the regions served by NoFRC, MFRC, and NeFRC, considering the distribution of major forest pests. Effort for biological control as a percentage of forest protection research is still low (less than 10%) at LFRC and PFRC in comparison with GLFRC where the 20% allocation seems more reasonable, given past successes, present knowledge, and future potential.

8. Recommendations are made for improving the planning and organization of the biological control program, for examining specific aspects of control agents, and for priority attention of target pests. In brief, the main recommendations are that:

- biological control research be increased from one-fifth to at least one-quarter of forest protection research; the research be concentrated on identified opportunities with key pests; and be integrated with silvicultural practices as an element of forest management.
- the key target insects be spruce budworm and bark beetles. For spruce budworm, where no long-term control has been discovered, emphasis should be on predators and parasitic insects that were inadequately tested in the past, and on virus diseases.
- more attention be given to environmental safety and to technology transfer.

- CFS research on predators and parasitic insects be restored, preferably by concentrating efforts in two teams, one in eastern Canada and one in western Canada.
- inundation release of predators or parasitic insects be tested practically.
- bacterial disease research be emphasized to ultimately provide the forest manager with a more reliable operational tool that can be used against spruce budworm for short-term control.
- virus disease work on sawflies be consolidated and reduced, and pesticide registrations be sought, especially for Douglas-fir tussock moth virus.
- fungal disease research be concentrated on production and field testing.

BIOLOGICAL CONTROL AND THE CANADIAN FORESTRY SERVICE

1. Objective of position paper

The objective of this position paper is to review the current CFS program of biological control of forest pests and suggest changes that might be made to strengthen the program during the next 5 years.

2. Definition of biological control of forest pests

Biological control is defined here as the direct use of living organisms to regulate the abundance of forest pests.

i) Scope

a) Pests. Insects are the main forest pests to be considered. Control of fungi seems unlikely on a large practical scale within the next 10 years. Limited success was found using *Peniophora gigantea* to control *Fomes annosus* in pines – it is, however, the biggest forestry success to date in temperate climates (Rishbeth 1971). *Trichoderma viride* has also been used. Baker and Cook (1974) have reviewed the field and, more recently, Wicker (1978) and Baker (1980). There are promising leads, for example, using hypovirulent strains of the pathogen to control chestnut blight (Anagnostakis 1981) or injecting the bacterium *Pseudomonas syringae* to control Dutch elm disease (Strobles 1981).

Control of dwarf mistletoe seems marginal. *Nectria macrospora* might curtail reproduction of hemlock dwarf mistletoe but no reliable way has been found to inoculate with this fungus (Smith and Funk 1980).

b) Control methods. Control of insects with living organisms includes the use of parasites (entomopathogens and so-called parasitoids) and predators. Methods of manipulation fall under three headings: (1) inoculation and natural spread of exotic control agents; (2) stimulation of indigenous control agents either by managing the environment or by breeding and releasing the control agents to increase their population; and (3) inundation of the environment with the control agent emphasizing its immediate control capability rather than its capacity to breed and sustain itself.

Pest control by autocidal methods such as introduction of sterile or genetically different individuals of the pest has shown slow progress with forest insects and is no

longer investigated within CFS. However, advances in genetic engineering may radically alter progress. Certain pests, especially those of high-value stands, such as plantations and seed orchards, may be particularly amenable to this approach.

Indirect methods of pest control, such as manipulating the host tree population of the pest insect, are excluded because they do not fall within the definition of biological control and are unlikely to show payoff in the next 10 years. It should be recognized that such methods are likely to be particularly important for control of diseases caused by fungi – for example, *Phellinus weirii* infects the roots of more Douglas-fir trees in pure stands than it does in mixed stands that include red alder.

Pheromones and insect growth regulators are excluded from consideration here because they are chemical methods of control. Similarly chemical insecticides mixed with biological insecticides are not classed as biological controls.

ii) Objective of biological control of forest pests

The objective of biological control is to reduce damage by forest pests to a tolerable level by regulating pest populations. Regulation includes reducing pest populations already causing intolerable damage (remedial treatments), as well as preventing pest populations from reaching unacceptable levels (preventive treatments). In achieving population regulation, biological control may either be used alone or in combination with other methods. Regulation upon application of the control agent may either be short term, which requires repeated applications, or may be long term because the control is self-perpetuating.

3. Biological control as a component of pest control

Forest renewal is urgently required if the forestry sector is to maintain its present position or expand. Conservation of our present forests as well as future ones is crucial to assure an adequate wood supply and protection from forest pests is thus an essential element of sound forest management.

i) Types of controls

Five major classes of control methods can conveniently be distinguished – quarantine to exclude exotic pests or restrict movement of native pests, planting desirable and pest-resistant trees, silvicultural practices, biological control, and chemical control that includes the use of pesticides.

ii) Choice of controls

This problem is situation-specific and generalizations are difficult. All possible control methods should be examined before making a decision. Three main questions are asked in evaluating a control method. Does it work? What does it cost? Is it socially acceptable? These are questions of technical feasibility, economic viability, and environmental compatability respectively. Brief amplification follows.

a) Technical feasibility should be estimated in terms of whether the pest control will reduce or contain tree damage at a tolerable level. Knowledge of the interaction between the control agent and the population dynamics of the pest is basic to our understanding of the control process. However, in the final analysis, the important measure is not how many insects are killed or debilitated, but how effectively tree damage is reduced to tolerable levels. This is a forest management decision.

b) Economic feasibility is a complex question requiring the input of economic specialists. Costs for the individual forest manager may be different from costs for the community, making analyses difficult. Nevertheless, all controls should be subjected to "best-guess" economic analyses for perspective. This approach has often been omitted in the past. Economics should not exclusively dictate research strategy. Ways are often found to reduce product costs of technical successes and factors such as legislation and product acceptance must be considered.

c) Environmental compatibility may often be the key factor. It comprises two aspects: environmental impact – the measurable effect on the environment including public health and safety, and social acceptability – the perceived risk to the environment and human health. Social acceptability is crucial, and disregarding it will almost certainly lead to failure of the control attempt. An example is the resistance to chemical insecticide spraying in many parts of Canada. Although New Brunswick relies heavily on chemical sprays, chemicals are not used on one-third of the area because it is classified as environmentally sensitive. Problems with social acceptability can be dealt with in one of two ways – alternative controls are found that are more acceptable, or society is educated to accept the controversial control through technology transfer.

4. Economics of biological control

i) Benefits related to research costs

Pest control with chemical insecticides is the norm against which other control methods are judged. However, economic comparisons between biological control

and conventional control with chemical pesticides are often lacking because the data are lacking. Where the data are obtained the benefit : cost perspective for biological control is impressive. A recent impartial economic assessment of 12 pest management projects in Australia, including wood wasp attack on pines and scarab beetle attack on eucalyptus trees, showed that, on average, a healthy $10.50 has been returned for every $1 invested even though 4 of the 12 projects failed to cover their cost (Marsden et al. 1980). For comparison, a common benefit : cost ratio quoted for chemical pesticides is 4 : 1 (Ordish 1976).

In Canada, the most detailed economic studies of control methods, including biological control, have been carried out with weeds. For example, diffuse and spotted knapweed in western Canada threatens wide areas of rangeland. The cost of using biological control was estimated at 28 PY (scientists) and $1.8 million, whereas control with the chemical picloram was estimated at $33 million (Harris and Cranston 1979).

The few available forestry statistics are equally impressive. For example, the European spruce sawfly threatened the entire spruce population of eastern Canada. It was a problem similar in magnitude to the spruce budworm outbreak today. Biological control at an estimated cost around 1940 of $300 000 is entirely effective to this day in containing the sawfly without need for further introductions of control agents. The project was helped by the fortuitous introduction of one of the control agents. For reference, the cost of chemical control of the spruce budworm is variously estimated at $100-200 million to date in 1950 to 1980 dollars and spraying of trees must continue. Chemical insecticides are, however, the most effective controls known at present.

Some costs are also available from the Commonwealth Institute of Biological Control (CIBC), the main agency from which Canada obtains its exotic parasitoids and predators. By 1967, the cost of running the CIBC was estimated at 1 million pounds sterling whereas aggregate benefits from major successes totalled 4.8 million pounds sterling (Simmonds 1967). The Department of Biological Control at the University of California produced figures claiming benefits of $115 million at a cost of $4.3 million (De Bach 1974).

ii) Production costs

The cost of producing biological control agents has been the subject of recent reports. The Stanford Research Institute concluded from an extensive investigation of novel pesticides (including some biological controls) that private industry was unlikely to produce these in competition with chemical pesticides because profits are much lower (Anon. 1977a).

Bacillus thuringiensis (B.t.), the main microbial pesticide now produced commercially, is apparently profitable because producers utilize spare fermenter capacity rather than specifically designing plants with high capital costs for exclusive B.t. production. The most recent study, by Schultz International for CFS, showed that dedicating a new plant exclusively to B.t. production would at least triple the cost of the present commercial product (Anon. 1981a). Unfortunately, other options such as renting fermenter time for producing B.t. or producing other products to defray capital costs were not considered, and a companion study on insect rearing costs was not completed.

Several viruses have also been produced, mainly in the United States, but it is difficult to estimate realistic production costs, partly because many producers lost money. Among viruses for forest pests, Douglas-fir tussock moth virus and gypsy moth virus have been produced in the United States at a contract price around $15/ha. Costs for virus production at FPMI, where the facility is small by commercial standards and the staff are paid as researchers, not production workers, are as follows: Douglas-fir tussock moth, $40/ha; spruce budworm, $250/ha; redheaded or European pine sawfly, $2/ha. Production of sawfly virus is inexpensive because it is conveniently produced in the field.

5. The place of biological control in integrated pest management

Of the five control methods detailed earlier for pest control, the use of chemical insecticides has been the most successful and dominates control strategies. Chemical insecticides are generally effective, fast-acting, versatile, and each application is reasonable in cost. Why, then, look further than chemical insecticides? Some insist the answer is because each application only provides short-term control, but other problems can also arise, such as harm to non-target organisms that include natural pest enemies, other wildlife, and humans; encouragement of secondary pests; development of pest resistance to chemicals; and accumulation of undesirable residues in the environment. These potential problems will increase as forest protection strategies with chemicals change. In New Brunswick, for example, merely keeping trees alive is no longer sufficient. Incremental growth must be maintained, requiring more extensive killing of spruce budworm. For these many reasons, alternative control strategies that will lower our degree of dependence on chemical insecticides are increasingly sought. This trend has turned attention to alternatives such as methods of biological control. Many strategies, either implicitly or explicitly, include biological control under terms such as integrated pest management.

Integrated pest management is defined as a combination of controls coordinated to reduce or prevent intolerable damage by pests. In forestry, for example, silvicultural, chemical, and biological control strategies may be combined. Integrated pest management is often considered particularly well suited to forestry where multiple use of the resource is practiced and higher damage levels are tolerated than in agriculture. When compared with the conventional use of chemical insecticides, integrated pest management appears to offer several potential advantages: it should work in combination with natural controls; less chemical is used; chemical costs are lowered; and any chances of producing chemically-resistant strains of insects are reduced. Also, because chemical use is reduced along with potential environmental contamination, integrated pest management should be more socially acceptable. Biological control can obviously play a pivotal role in integrated pest management, perhaps particularly in forestry applications, because there is some evidence that automatic, self-perpetuating controls are favored by stable, diverse environments. However, it must also be recognized that biological controls, including integrated pest management strategies, entail manipulations of complex biological interactions. Such approaches will require more in-depth understanding of the dynamics of pest populations (e.g. Norton and Holling 1976; Berryman and Safranyik 1980), including the interaction with natural control factors, than is the case with chemical control strategies.

6. Recent assessments of biological control research by outside agencies

Many reports and workshops have been held in the last few years that address the importance of biological pest control. For example, in the United States, the National Research Council, an official but independent advisor to the federal government, presented an extensive five-volume review of pest control practices and prospects. Several "crops" were examined in detail, one of which was trees. The report recommended that "research on forest pest control be closely coordinated with research on silviculture and forest management" and that "increased support be provided on biological control" (Anon. 1975). A later report by the U.S. Department of Agriculture commissioned by President Carter to encourage development and application of natural biological controls listed eleven recommendations for improved support (Anon. 1978). In essence these recommendations were:

- promote biological control activities through contracts and grants and provide technical assistance to potential users

- give priority to field trials and to production, formulation, storage, and application technology
- develop methodology to appraise not only technical feasibility but also economic-environmental aspects
- review pest control legislation to encourage biological control
- set up national coordination including state–federal–industry programs and a national information retrieval system
- expand foreign explorations for biological control agents
- expand basic research, especially on insect population dynamics

Two recent international workshops have dealt specifically with microbial control of insect pests (Allen et al. 1978; Anon. 1980a); the more recent workshop was designed for the sponsor to capitalize on what it considered to be a promising growth area of applied research.

Recently an international seminar on all aspects of biological control was held by the U.S. Department of Agriculture at its main research centre in Beltsville, Maryland. Each year one key subject is chosen for this major seminar. In 1980 it was biological control.

Canadian reports also favor more biological control research in entomopathogen research. The Feb. 18, 1981, biotechnology task-force report to the Minister of State for Science and Technology stressed the importance of biological controls for forest protection and recommended that CFS efforts be strengthened (Anon 1981d). During the summer of 1981, the Canadian Environmental Advisory Council submitted a report to the Minister of Environment strongly advocating increased support for biological control as a pest control option.

Undoubtedly, part of the widespread interest in biological control is because chemical insecticides, while providing an essential and effective means of pest control, are not without limitations and are only one of many control options. More efficient and effective alternatives (not necessarily replacements) for chemical insecticides are needed, a point forcefully made by Carrow (1981) "so that our exclusive reliance on chemicals can be reduced." A similar view was expressed in the Department of Environment's policy statement on aerial spraying issued in 1977 (Anon. 1977b).

7. The global success and potential of biological control

a) Consider first the introduction of parasitoids and predators (so-called classical biological control). Worldwide, natural enemy introductions have resulted in

substantial to complete control of upwards of 100 pest species (van den Bosch 1975). In Canada, successes with biological control using predators or parasitoids up to 1968 have been summarized by Munroe (1971). Up to 1958, attempts were made to control 24 agricultural pests of which 10 were considered successful; in forestry 9 of 25 attempts were rated sucessful. From 1959 to 1968 forestry researchers were considered successful in continued work to control 5 pests out of 7 attempts; in agriculture, with a diminished research effort, only 1 of 4 attempts was rated successful; and of 10 additional attempts, 8 were failures. Reviews of work up to 1980 in Canada are now being undertaken and should be ready in 1982.

Intensity of effort has varied enormously (for example, in CFS most of the effort has been against introduced pests in the belief that they may not have brought all their natural enemies) and the inescapable conclusion is that success has rewarded effort. This conclusion is equally valid worldwide. General postulates about best and worst conditions for biological control with predators–parasitoids are based on case histories and largely reflect the uneven effort devoted to biological control around the world. There appear to be few theoretical grounds for making generalizations and exceptions can invariably be found (De Bach 1964). The most useful conclusions to be drawn are that temperate continental areas provide good environments for biological control and successes in biological control are more numerous where effort is more intensive.

The potential for control of forest pests using biological control methods with introducted predators–parasitoids must therefore be rated as high, particularly as a component of integrated pest management, especially when more knowledge is obtained on how the behavior of pest and control agent affects insect population dynamics. Each decision to consider biological control is situation-specific with technical, economic, and environmental aspects.

Augmentation of native predators–parasitoids, particularly by mass production and inundation releases, has not been widely practiced in North America despite the success claimed in Russia and China. For example, release of the egg parasitoid *Trichogramma evanescens* against pine budworm pests in Russia reduced damaged buds by 50%; and in China, *Trichogramma dendrolimi* released against *Dendrolimus sibericus*, a serious pest of pine, larch, and spruce, reduced infestations from 63% of trees to only 1% and no further outbreaks that usually occur in 10-year cycles have been reported (Bennett 1980). Judging by these examples, technical success for suitable pests must be rated as promising.

b) Introduction of entomopathogens is a developed method of pest control. Bacterial products such as B.t. are used around the world, including Canada, for control of

lepidopterous pests. Viral entomopathogens are also used widely. Viruses of Douglas-fir tussock moth (*Orgyia pseudotsugata*) and gypsy moth (*Lymantria dispar*) have been produced commercially in North America. Sawfly viruses such as the redheaded pine sawfly (*Neodiprion lecontei*) and European pine sawfly (*Neodiprion sertifer*) work well in the field, particularly in Canada, and *N. sertifer* virus is produced commercially in Finland. Viruses for *Dendrolimus* spp. pine defoliators are used in Japan and China. For "crops" other than trees, viruses that attack *Heliothis* pests of cotton and tobacco are produced and registered commercially in the U.S. and Australia. Viruses of pests such as *Trichoplusia ni* that attack cotton, cole, and other crops are near to commercial production in the U.S. and are already used in Colombia as first choice insecticides because of their effectiveness. There are many other examples.

A number of fungi are also used as entomopathogens. *Beauveria bassiana* is used against forest pests in Russia and China. On "crops" other than trees, *Verticillium lecanii* is now produced commercially in western Europe for use against some aphids. *Hirsutella thompsonii* is used in North America against mites (not insects). *Metarrhizium anisopliae* is used against insect pests in China and South America and other fungi such as *Nomurea rileyi* and *Entomophthora* spp. are widely used experimentally, mainly on pests of agricultural crops. *Cordyceps militaris* has been tried but is unproven on forest lepidoptera in Canada.

Only one protozoan entomopathogen has been developed for widespread field use. *Nosema locusta* with a bait is registered for grasshopper control.

The potential for control of forest pests with entomopathogens must also be rated as high, particularly as a component of integrated pest management. It is important to choose the most promising combination of pest species and entomapathogen.

8. Biological Control and the Canadian Forestry Service

i) Rationale

Biological control as an aspect of forest management fits perfectly into the CFS research mandate in Environment Canada. The work is national in scope; it is complex and requires a mixture of expertise not avilable in small organisations; and it requires collaboration with other national organisations such as Agriculture Canada, international organisations such as the CIBC, and foreign national organizations such as the USDA-FS.

Researchers in CFS are, however, unclear about the emphasis that CFS places on biological control. A clear statement of policy would help, possibly following the

strategy (not the specific recommendations) of the Director of the Northeastern Area, State, and Private Forestry USDA-FS who considered five alternative pest control strategies and made the decision to "increase (effort in) silviculture and utilization marketing, decrease (effort in) chemical insecticides...and increase (effort in) biological insecticides" (Schacht 1981).

ii) CFS and the CIBC

The CFS has traditionally paid the Commonwealth Institute of Biological Control (CIBC), part of the Commonwealth Agricultural Bureaux, to collect and ship promising parasitoids–predators to Canada. The CIBC station in Delémont, Switzerland, has been used because geographic conditions in this European region are considered similar to Canadian conditions. The arrangement is efficient because it utilizes local experts and inexpensive because the CFS contract only covers about half of CIBC's costs and stationing Canadians in Europe would at least double collection costs. Unfortunately, as a result of a decrease of interest by CFS, the CIBC Delémont station recently dismissed its only full-time forest entomologist; CFS work is now carried out by part-time staff. Apparently, a permanent forest entomologist would be hired if CFS insisted and provided financial support through contracts.

The CFS method of selecting collections from CIBC has been to canvass research scientists for their needs, through their program managers, and submit a consolidated request for work. Rarely does the scientist requesting the material become involved in the actual collection to learn more of the potential parasitoid–predator's biology. Sometimes CIBC provides a literature review of European knowledge on the predator–parasitoid.

iii) CFS and Agriculture Canada

No formal contacts exist between organisations to expedite biological control research. Contact is between individual scientists. Agriculture Canada and CFS cooperate through the Federal Interdepartmental Committee on Pesticides in drawing up protocols and data requirements for entomopathogen registration. Agriculture Canada is responsible for controlling all imports of biological control agents; handling may be delegated to CFS officers with adequate quarantine facilities such as those at GLFRC.

iv) CFS and the USDA-FS

There are no regular formal consultations by CFS and USDA-FS on biological control work. For entomopathogens, contact is made through working groups such as those of the Society of Invertebrate Pathology. The North American Forestry

Commission (Canada, Mexico, and U.S.) working group on insects and diseases plans to hold a workshop on biological control at Sault Ste. Marie in 1982. CANUSA, for spruce budworms, contains some biological control aspects. Some U.S. projects encourage Canadian contributions from individual scientists, e.g. Project S-135 entitled "Microbial Agents for use in Integrated Pest Management." The U.S. "big bug" programs on southern pine bark beetle (*Dendroctonus frontalis*) and gypsy moth (*Lymantria dispar*) allowed limited, mostly informal, Canadian participation; with Douglas-fir tussock moth (*Orgyia pseudotsugata*) the USDA-FS and CFS, together with the B.C. Forest Service, cooperated in 1975-76 on field trials of control methods, including biological controls, near Kamloops, B.C. A letter of agreement was signed between PFRC and Region 6 of the USDA-FS and this work is cited as pioneering international cooperation on a major forest insect pest (Anon. 1980b).

Canada and the U.S. used to review their biological programs together approximately every 2 years to exchange information among coordinators. The last meeting was held in Newark, Delaware, in 1974. There has been recent interest in reviving these exchanges.

v) CFS successes with biological control

Some important technical successes by federal scientists include biological control of the following: larch sawfly (*Pristiphora erichsonii*), introduced pine sawfly (*Diprion similis*), European spruce sawfly (*Gilpinia hercyniae*), satin moth (*Leucoma salicis*), larch casebearer (*Coleophora laricella*), winter moth (*Operophtera brumata*), redheaded pine sawfly (*Neodiprion lecontei*), European pine sawfly (*Neodiprion sertifer*), Swaine jack pine sawfly (*Neodiprion swainei*), moutain ash sawfly (*Pristiphora geniculata*), white-marked tussock moth (*Orgyia leucostigma*), and Douglas-fir tussock moth (*Orgyia pseudotsugata*). In addition, microbial insecticides like B.t. show potential for controlling many lepidopterous forest pests provided they are applied like chemical insecticides (repeat applications are needed) and application techniques can be improved to make control more reliable; pests in this category include spruce budworm (*Choristoneura fumiferana*), forest tent caterpillar (*Malacosoma disstria*), and hemlock looper (*Lambdina fiscellaria fiscellaria*).

Many more examples could be given, showing varying degrees of technical success. Indeed, few pest insects have been studied that show no response to attempts at biological control.

Economic success has not often been evaluated. Winter moth control is, however, particularly well documented: control costs estimated around 1970 were

$500 000. Potential loss to the economy just in destruction of red oak was $45 million and these losses were already $7 million when controls were introduced. The spectacular success in controlling European spruce sawfly has already been cited. Total control costs estimated around 1940 were $300 000 when already half the spruce in the Gaspé had been destroyed.

Social–environmental compatibility of all these control attempts must be rated as good. Microbial insecticides, however, may be questioned if they become (even though incorrectly) labelled as germs or possible carcinogens in mammals.

vi) CFS and production facilities

A constant problem in biological control is the establishment of suitable production facilities because the pesticide production industry understandably favors chemical insecticides where profits are higher (Anon 1977). Even B.t. production utilizing spare fermenters is geared to agricultural insects. Optimal production conditions for biological control agents such as microbial strains for forest insects will be different, probably leading to improvements of at least 100-fold. Unfortunately, nobody has taken responsibility for pursuing this work. Production of insects for either viruses or predators–parasitoids also needs to be automated for economical large-scale production. This level of production has been carried out abroad with sterile insects released to control Mediterranean fruit fly (50 million/day), melon fly (15 million/day), and stable fly (1 million/day). Again, nobody in Canada has taken responsibility for pursuing this work. Perhaps the best solution would be for cooperative involvement by the federal and provincial governments with the forest industry. In the meantime, CFS should try to promote the development of Canadian production facilities as needs expand–it is not technology that can readily be bought abroad but must be developed for Canadian conditions.

9. Current CFS work in biological control

i) Breakdown by establishment

The present division of biological control activities between establishments is shown in Table 1. FPMI, NoFRC, and PNFI are exclusively concerned with entomopathogens while GLFRC and NeFRC only work with predators–parasitoids. PFRC LFRC, and, to a small extent, MFRC conduct control work with both entomopathogens and predators–parasitoids.

About 60% of the biological control funds are spent by FPMI (Table 2) with LFRC spending about 20% of the funds, and PFRC and GLFRC each spending nearly 10%. NoFRC, MFRC, NeFRC, and PNFI together only spend about 5% of the biological control funds. Allocations at NoFRC, MFRC, and NeFRC seem too low considering their proximity to major forest pests (see later) and the importance of including biological methods as a control option.

Resources allocated to biological control personnel are divided nearly equally among establishments (Table 2). Of the four major establishments involved in biological control research, LFRC provides roughly one-third more resources for each person year than FPMI.

ii) Breakdown by control agent

The person years devoted to each type of control agent at each establishment are shown in Table 3; because more than three-quarters of the manpower is devoted just to entomopathogens, this category is further subdivided in Table 4. Most of the bacterial work is conducted at FPMI and LFRC; work with viruses and protozoa is centered at FPMI; fungal work is largely at FPMI with a substantial contribution from PFRC; most work with predators–parasitoids is at GLFRC and LFRC with some work being done at PFRC and NeFRC. The most obvious anomaly is the poor support for predator–parasitoid work. Indeed, it is debatable whether CFS still has a "critical mass" of future expertise in this area. Only two laboratories provide more than 1 PY for this work yet CFS has had several successes with this control method. There are no theoretical reasons to discount further success because social–environmental acceptability should be a particular advantage and registration – a costly and uncertain procedure –is not required. Concentration of entomopathogen work at FPMI makes efficient use of CFS resources, particularly for basic research and handling of insecticide registration procedures.

The manpower allocation to individual biological control agents throughout CFS is shown in Table 5. Viruses take about 30% of the biological control manpower with bacteria, fungi, and predators–parasitoids each taking about 20% and protozoa about 10% of the manpower.

iii) Breakdown by target pest

Table 6 summarizes the person years in biological control allocated to individual target pests. Figures are approximate and vary from year to year. In some areas of FPMI work, the program plans do not indicate the proportion of effort devoted to each target pest. For example, discussions with the project leader of virology revealed that about 50% of resources are for sawflies and 50% largely for spruce budworm. It would help if this information were in the program plan.

About 60% of biological control manpower in CFS is allocated to spruce budworm, comprising roughly one-third to B.t., one-quarter to viruses, slightly less to fungi, and the remainder to protozoa and (predatory) red ants. Note, however, that this 60% figure is obtained by allocating the entire "support" research at FPMI (one-quarter of the 60%) to spruce budworm. The European pine sawfly and redheaded pine sawfly account for almost 20% of the manpower, about two-thirds of which is devoted to viruses and the remainder to parasitoids. Gypsy moth (parasitoids), bark beetles (fungi), and Douglas-fir tussock moth (virus) each have about 5% of the manpower. Several observations made here will be expanded later.

Research resources on bark beetle control seem low considering the pest's economic and environmental importance, whereas sawfly resources seem high, particularly for parasitoid work where viruses are so effective. For spruce budworm research, B.t. is the nearest to reliable, short-term operational control. Intensified efforts should complete this work even at the temporary expense of any additional fungal work where little progress in field control has been made (little progress has also been made with protozoa but protozoa are the most common parasites of spruce budworm and resources are already trimmed to one scientist). Futhermore, research on long-term control should be strengthened, looking at the aspects both of hastening population collapse and of maintaining endemic levels of the pest where these occur.

iv) Breakdown by age of researcher

Detailed data are not available here. Broadly speaking, age distribution of researchers in entomopathogen research is even but in predator–parasitoid research it is badly skewed to the older end and valuable expertise will soon be lost with retirements.

v) Percentage of CFS forest protection research devoted to biological control

Table 7 summarizes the percentage of each establishment's forest protection research budget devoted to biological control research. When the FIDS component (a major cost item included in forest protection) is removed, the figures show that FPMI spends approximately 45% of its forest protection budget on biological control research whereas GLFRC spends 20% and each of PFRC, LFRC, and MFRC (largely tree diseases) are approaching 10%. Considering their proximity to major forest pests, effort devoted to the biological control option must be considered low for PFRC and LFRC and particularly low for MFRC, NeFRC, and NoFRC. In total, about one-fifth of the forest protection research budget throughout CFS is spent on biological control of forest pests; this seems low considering past success, present knowledge, and future potential. A further refinement removing forest fire research from the calculation does not substantially alter any of these numbers.

10. Planning for future biological control work in CFS

i) Past planning experience

It appears that in the past many research workers have selected the target pest and biological control agent largely on the basis of academic background or research interest. The choice has often been insect- or agent-oriented rather than based on a forest management need. Committee reviews set up to evaluate the choice and monitor progress in achieving control have apparently endorsed this approach. More mission-oriented work has been carried out in recent years.

Unfortunately, biological control attempts were often poorly planned and never really gave the agent a fair chance of success. As a result, we have insufficient knowledge of the degree of control success or the mechanism of action.

Special mention must be made of predator–parasitoid research. Many theories exist on which are the most tractable pests, the best geographical locations, the best crops, and the best parasitoids or predators for biological control. The theories are based on case histories but exceptions to theory lead experts to disagree on just how to predict likely success (e.g., Debach 1964). Some of these questionable theories may even have been used in the past in rejecting control agents or target pests. There is a theory that native pests are unlikely to be controlled biologically. Yet, as Munroe (1971) has pointed out, this belief ignores bolstering concentrations of natural enemies at critical times; judgments are frequently erroneous on whether pests from different countries are in fact the same; terminologies "native" and "introduced" are relative; and because introduced pests can be so destructive to "native" trees why cannot introduced predators–parasitoids be destructive to native pests? Indeed, Pimentel (1963) produced a list of successes against native pests and recently U.S. entomologists claimed control of a native forest pest using an unpromising introduced parasitoid from a host of a different genus (Bustillo and Drooz 1977). Clearly such theories can be misleading in predicting success.

ii) Future strategies

a) Setting of control priorities is a forest management decision. It involves first, identifying the unacceptable damage to tree stands or species; second, if pests are responsible, identifying and characterizing the pests; and third, selecting the types of pest control that should be considered from examination of their technical and economic feasibility, and social acceptability. In considering biological control, Table 8 indicates past major CFS technical successes with biological control agents and compares this with the current manpower devoted to each control agent. Note that almost one-third of the

manpower is devoted to control agents that are unsuccessful to date. The main reason advanced for lack of success is that there have been no serious attempts made to use these pathogens in the field.

b) Major research needs by individual biological control agent are in Table 9, constructed as a general rating of predicted success for each biological control agent. The table serves as a framework for highlighting research needs – more detail is in the annual project statements and biennial program reviews. Amplification of the ratings follows.

I Predators-parasitoids – Technical success must generally be rated good, based on past successes. Each problem is situation-specific and the most important need is for careful organization of research, especially in measuring impact of the control attempt (see 10(ii)(d)).

Economic success should be outstanding, depending on the scope of research and pest problems, if control results from inoculative releases of exotic predators–parasitoids that require little rearing. Inundatory releases, however, require costing of rearing methods; this is an important need. The Chinese and Russian experiences with inundatory releases are considered difficult to extrapolate to North American conditions.

Social–economic acceptability should be good with the possible exception of predators like red ants; they can be a nuisance to many animals, including humans, and their nests are obtrusive. This situation needs evaluating.

II Bacteria – B.t. is widely used for short-term control yet technical success is still variable. There is urgent need to complete our work – forest managers want this alternative as soon as possible. A key need is to identify factors for variability starting from B.t. delivery to the spray plane, through deposition on the tree from the plane, to B.t. field life on the tree (e.g., Harper 1979). Factors should be given priorities and research needs identified after applying present CFS research findings. Present indications are that B.t. provides reliable control when applied at the correct time, in sufficient quantity, and with an efficient delivery system.

Economic needs center on reduction of transported volumes using more concentrated formulations, and on strain-production methods for more potency (for example, penicillin, another microbial product, where prices fell 5000-fold in 12 years of focussed research). Recently, a strain of B.t. has been found for *Heliothis* spp. pests that is 100 times more potent than the present industrial strain.

Social–environmental acceptability seems satisfactory based on presently registered B.t. products.

III Viruses – Technical success varies from outstanding with some sawflies to variable with spruce budworm. For the latter, high dosages resulting from poor infectivity seem critical, especially because a natural viral epizootic has never been observed. Thus, a key need with spruce budworm is to improve infectivity. Production of viruses also needs technical attention. Manual handling of live insects, the present method, is inefficient and costly. Small insects are particularly difficult to handle and alternatives should be sought. Tissue culture techniques are potentially more efficient; problems to be addressed here include delicacy of the cells and production of "aberrant" virus.

The key economic need is for cheaper production methods using either *in vivo* or *in vitro* techniques. Tissue culture methods, especially, require cheaper media. Present costs are at least 20 times too high.

Social–environmental acceptability ought to be satisfactory although possibilities of oncogeny and the potential for inducing mutation must also be carefully evaluated.

No virus is yet registered for use as a pesticide in Canada. The first petition for red-headed pine sawfly was submitted in March 1981. Registration data for other viruses with demonstrated efficiency need to be submitted. Cooperation with the USDA-FS should be maintained for information exchange.

IV Fungi – Technical problems center on production of certain fungi, field survival of the fungi, and their ability to control insect populations by artificial inoculation; for example, conditions may be too dry for spore germination except perhaps in the cool, damp climate of Newfoundland. Natural fungal epizootics are known; a recent example was the eastern hemlock looper in Newfoundland. Economic needs center on production and application methods. Social and environmental concerns include respiratory problems and center especially on allergic reactions in humans, a problem recognized in China when using fungi on forest pests.

V Protozoa – These debilitate rather than kill the pest insect. They can be very common, for example, in spruce budworm and may thus act synergistically with other control agents. The most important research need is to make use of these interactions for pest control. If they are field inoculated for pest control (those involved with this work doubt that they will ever be used alone), technical problems center on production methods as well as assessing the impact of artificial infection

on pest populations. Economic problems center on production and application; special social–environmental concerns have not been identified.

VI Others – Rickettsia and nematodes have received little attention from Canadian forest entomologists. Rickettsia work carries risk of human disease and no research should be undertaken. However, nematodes are considered to be an imporant mortality factor for some bark beetles (Anon. 1978). Recent tests in Newfoundland showed that the nematode *Heterorhabditis heliothidis* killed spruce budworm. More detailed epidemiological studies are needed to evaluate their natural role in control of forest pests.

c) Major research needs by insect pest – Emphasis in selecting pests is taken from the national FIDS report on 1980 conditions.

I Spruce budworm – This insect is the dominant forest pest problem in Canada. Long-term control is urgently needed. Losses in the current outbreak exceed 5 years of softwood harvest in eastern Canada. The CANUSA program was thus set up with two objectives (as stated in the Memorandum of Understanding) –to control spruce budworms and to manage susceptible forests. Yet, of the annual 100 PY devoted to spruce budworm research, virtually no resources are assigned to direct long-term control. Baskerville lists 15 tactics for dealing with spruce budworm (Baskerville 1976). Only two, socially questioned chemical larvicides and B.t., are operational but these are for foliage protection and must be reapplied; they are not long-term controls. Among other tactics, insect growth regulators may eventually also protect foliage if nontarget toxicity problems are overcome. Long-term control using field entomopathogens seems unlikely. Viruses, so far the most promising, do not cause epizootics: they act like B.t. or chemicals. Genetic manipulation of spruce budworm or use of pheromones do not seem suitable for long-term control. Widespread management of host tree populations or altering the timing of bud-flush seem even more remote possibilities in the next 50 years. In brief, none of our current efforts in these areas could be classed as promising long-term control attempts.

Predator–parasitoid manipulations are the only remaining control options. Birds are the main predators but population augmentation with nesting boxes, for example, seems impractical. Augmentation of native parasitoids is neglected perhaps because rearing and application costs are considered too high – yet Baskerville rates suppression potential in this area as high. Even with exotic parasitoids, CFS plans no work because earlier introductions failed – "the CFS made

repeated attempts to naturalize exotic parasites but not one of the 16 species survived" (Miller and Varty 1975). The data, however, require closer scrutiny. In many cases, low numbers (as few as 3 individuals) were released (Anon. 1962) or the timing of the releases was incorrect (Miller 1963). Indeed, for all 16 species "the release and recovery techniques were insufficiently documented and we do not know why these attempts failed" (Cameron and Renault 1973). Regardless of these shortcomings, many entomologists consider control of native pests with introduced parasitoids to be hopeless; yet Pimentel (1963) provides a list of successes and recently, U.S. workers controlled a native Colombian forest pest with an introduced U.S. egg parasitoid from an entirely different host (Bustilla and Drooz 1977). As Baskerville points out, "many scientists consider the technique to have a low probability of success although most agree there are few data on which to base definitive conclusions." The above data suggest that CFS has not tried hard enough to assess control potential. There seems little point in further assessing what has been done because important data are obviously lacking. What is needed now is a fresh unbiased start to test these control methods. The field releases should be supported by studies of population dynamics (target pest and control agent) and might include novel approaches, such as enhancement of parasitoid activity with kiaromones. If CFS had good reasons to undertake this work in the past, these reasons are even more valid today. As Baskerville points out, "absolutely no one is enthusiastic about long-term protection with chemical insecticides, so the problem of developing another approach must be faced."

II Bark beetles – These are the most serious insect pests of mature conifers in western Canada. Even in eastern Canada, the eastern larch beetle (*Dendroctonus simplex*) has destroyed 500 000 m^3 of tamarack. The potential loss to the British Columbia economy in 1979 from the mountain pine beetle (*Dendroctonus ponderosae*) is estimated at $700 million. More than 14 million trees, with a gross volume near 8 million m^3, were killed over an area of 156 000 ha (Anon. 1981b); this figure represents about 10% of the annual allowable cut of all species in B.C. Recommended controls include sanitation logging and baited trap trees. These are often "intended to buy time in the hope that the infestations will be affected by natural factors" (Anon. 1981c). Extensive spraying of chemical insecticides is not technically feasible and thus biological controls are potentially more attractive for both short- and long-term controls. However, the population biology of predators–parasitoids and entomopathogens has hardly been studied (Anon. 1981b). The role of these agents in regulation of beetle population is not clearly understood nor is the

potential benefit known, using either remedial or preventive treatments. Introductions of exotic predators–parasitoids have also been neglected, yet old reports from Germany, for example, show 90% parasitism in some European bark beetle populations at the time of population collapse (Wellenstein 1954), although the parasitoids alone might not have caused the collapse. This neglect of predators–parasitoids is all the more surprising when promising establishments against pine bark beetles (*Hylastes ater*) are reported from New Zealand, using a pteromalid parasitoid and clerid predator shipped from Austria in 1975 (Milligan 1978). Some of the most detailed information on bark beetle predators–parasitoids–entomopathogens has been collected on southern pine bark beetles in the U.S., but even in this instance, control attempts utilizing this knowledge are few (Thatcher et al. 1980). Similar comments apply to control attempts with the western pine beetle (*Dendroctonus brevicomis*) (Stark and Dahlsten 1970).

CFS control attempts using entomopathogens have centered around *Beauveria bassiana*. The fungus is lethal to the insect but no way has been found of ensuring that the insect picks up the fungus in the field. Yet one of the most successful examples, in this case with the rhinoceros beetle attacking coconut palms in Western Samoa, involved use of a virus and a fungus (*Metarrhizium anisopliae*). The fungus was applied to large accessible breeding sites, where it successfully controlled the beetle, while the virus was used for inaccessible places. However, even after a viral epizootic, beetle populations had to be further suppressed by releasing virus-infected beetles (Marschall 1980). This application apparently resulted in excellent control. Clearly much work on biological control remains to be done with bark beetles ; the potential for success appears good.

III Cone and seed insects – These are pests of increasing economic importance, particularly as they affect forest renewal. In Douglas-fir, for instance, 50–90% of the cones were considered unsuitable in parts of B.C., as a result of insect attack. Figures for Englemann and white spruce in B.C. are similar, and in Ontario, 18–55% of black spruce cones sampled were damaged. The only CFS biological control work here is with *Beauveria bassiana* but the work is preliminary. Further information is needed on the biology of the pest insect. After the acquisition of this information, feasibility studies should be undertaken on biological control as well as other control methods. The integrated pest management strategy in seed orchards that might include biological control would have to ensure almost 100% protection because of the high value of the crop and should include treating areas adjacent to seed orchards.

IV Sawflies – These insects have proved particularly amenable to biological control in the past to the point where most no longer cause serious economic losses. CFS work in this area should be consolidated, but there seems little reason for expansion of present efforts. However, predictions of future outbreaks are needed because sawflies have caused major economic losses. Indeed, these predictions are needed for most of our potential forest pests.

V Hemlock looper – This insect has caused important economic losses although Newfoundland populations are presently controlled by natural factors including *Winthemia occidentis*, a parasitic fly introduced from B.C., and disease caused by *Entomophthora*, a species of fungi. Predictions of future outbreaks are needed to assess priorities in control attempts.

VI Forest tent caterpillar – This insect and related species have defoliated almost one-half of the susceptible hardwoods (mainly poplar) in New Brunswick. Many sugar maple groves in southern Quebec have been severely defoliated. This insect seems particularly susceptible to weather (e.g., in northern Ontario) or parasitism (leading to collapse in B.C.). It is also susceptible to B.t. Moderate CFS effort with a biological control option would probably be successful should the economic threat or public nuisance be considered significant.

VII Other insects – Although the list of potential pests could be expanded enormously, the economic importance of the pests, relative to the ones already cited, make the exercise largely academic given limited CFS resources. Populations of Douglas-fir tussock moth regularly irrupt although some claim this only occurs where Douglas-fir reaches the limits of its range (e.g., the drier areas preferred by ponderosa pine); replacement with other species may then be the logical approach. The CFS has already developed an excellent management system for this insect comprising pheromone traps to monitor populations and a virus for control of outbreaks. The virus, however, urgently needs registering for operational use. Another important insect, the gypsy moth, devastates hardwood forests in the northeastern U.S. but has had little effect so far in Canada. Little more than a watching brief or continuation of work at its present low level seems required for CFS at the moment; once again reliable predictions of outbreaks are needed, especially since recent observations suggest a population irruption might be imminent in parts of Canada.

d) Research strategy – The research strategy to assess technical success of biological controls must be carefully planned to involve wide consultation and review at all stages.

For entomopathogens the essential steps are isolation of the microorganism, characterization, laboratory virulence tests, production, formulation, and field testing. Pragmatic decisions on the amount and timing of supporting basic research (mode of action and other matters) must be made continuously.

Planning of predator–parasitoid introductions is particularly complex and, as a result of the number of factors involved, decisions must be made on empirical rather than theoretical bases. This first involves deciding whether to enhance or inundate the pests' environment with native predators–parasitoids or to introduce exotic species. Studies of pest epidemiology, pest origin, and modelling of population dynamics would all contribute. If native predators–parasitoids are chosen, studies of their behavior–taxonomy and rearing techniques would follow. Monitoring of releases is needed to accurately assess their impact, perhaps using modelling. If introduced predators–parasitoids are used, decisions are needed on where to look (climate, tree species, insect pest), how to collect potential candidates, how to ship and rear them, how to test for host-environmental compatibility, and how to release and monitor the impact of the releases (determining whether the introduced agent is established and then how this affects tree damage, possibly including modelling of insect population dynamics). Clearly, planning of the work is so complex that frequent consultation and reassessments are essential for efficient execution of research.

e) Technology transfer – In Canada, the identification and research on biological control of forest pests are carried out mainly by CFS. Companies, associations, and provinces generally lack the resources to initiate and coordinate biological control research at the level needed to make it effective. However, companies and provinces should conduct the needed development to refine operational use of the controls. Production of registered materials or predators–parasitoids for operational use should also be mainly their responsibility. This progression of responsibility requires efficient transfer of CFS know-how as well as public education on the control methods.

11. Recommendations for Strengthening the CFS Biological Control Program

i) General Organization of Program

1. That the Assistant Deputy Minister of CFS make a statement on program direction, both for internal and external use, on the emphasis to be given to biological control and integrated pest management as a component of forest protection research.

2. That the present allocation of forest protection research resources to biological control research be increased from one-fifth to at least one-quarter of the budget, to revitalize CFS capabilities in predator–parasitoid control, and address urgent needs with control options for specific pests outlined in section 10 (ii)(c.)

3. That biological control research be integrated as part of a forest management research plan along with other pest control strategies, especially silvicultural practices. This plan should include combining control assessment with damage appraisal, using FIDS. It should also include some economic assessments.

4. That CFS program plans be organized so that biological control research as defined in this report is a discrete activity, within forest protection research.

5. That CFS program plans show the proportion of effort (in this case in biological control) devoted to each target pest.

6. That environmental–health aspects of control methods be explicitly addressed in planning documentation early in the research program and resources allocated for needed information.

7. That the strategy for transferring technology for public education and industrial-operational development be included in planning documentation. This information should be specific once the control shows technical feasibility.

8. That modelling of pest insect population dynamics be linked with biological control research, particularly with predators–parasitoids.

9. That all biological control attempts by CFS to date be evaluated in detail in terms of technical, economic, and social success (underway as a CIBC publication).

10. That division of entomopathogen research responsibilities between FPMI and the regional establishments be delineated where this improves work efficiency; FPMI should maintain more basic research than regional establishments.

11. That registration and related use aspects of control agents (entomopathogens in the present context) be handled by FPMI in consultation with appropriate regional establishments.

12. That scientists prepare suggestions for management on how closer ties can be established between CFS biological control research and similar work in Agriculture Canada, and if possible, also with research of the USDA-FS, and with university research workers.

13. That NoFRC, MFRC, and NeFRC restore their capacity for conducting biological control research (as defined in this report) to at least match the resources of PFRC or GLFRC. Certain resources may be pooled depending on the following recommendation.

14. That consideration be given to setting up two centers of expertise in predator–parasitioid control, one in eastern Canada and one in western Canada.

15. That CFS, through Headquarters, maintain an interest in establishing Canadian facilities for producing biological control agents.

ii) The control agents for the program

a) Predators–parasitoids

16. That at least 10 PY of resources be added to predator–parasitoid research to restore the viability of this program and better reflect the relative potential of this method for successful control.

17. That FIDS be used to monitor operational control attempts (a) on success in establishing agents, and (b) on impact on tree damage.

18. That CFS support for CIBC be strengthened by (a) requesting a permanent forest entomologist be hired at Delémont, and (b) planning to commit up to 20% more funds for each of the next 5 years to support collection activities as specific projects expand.

19. That collecting locations other than Europe be explicitly considered in planning documentation for introductions of exotic predators–parasitoids (this is done automatically only for exotic pests from non-European countries).

20. That regional CFS scientists responsible for attempting the introductions be encouraged to help with collection to learn more of the biology of the predators–parasitoids.

21. That the population dynamics of predators–parasitoids be specifically detailed in each control attempt.

22. That the Biosystematic Research Institute of Agriculture Canada in Ottawa be involved in each control attempt with the involvement included in planning documentation to ensure the identity of native-foreign hosts and predators–parasitoids.

23. That planning of control attempts at the regional establishments include input from fellow specialists across the country and follow a documented progression such as the one described in this report. This progression should include all phases, from selecting the method of introduction, to rearing methods, monitoring introductions, and measuring their success.

24. That documentary organization of projects include planning to transfer practical expertise from staff soon to retire to their replacements.

25. That LFRC review its research using red ants as spruce budworm predators, especially by assessing the social acceptability of this method.

26. That predator–parasitoid work on sawflies be consolidated and terminated.

27. That predator–parasitoid control of bark beetles be assessed by PFRC.

28. That predator–parasitoid control of spruce budworm be undertaken. Part of this work may include the following recommendation.

29. That the control technique of inundation release be practically tested in Canada against a selected isolated pest outbreak (two possibilities were given earlier). This test should include rearing and application costs.

30. That feasibility studies on biological control of cone and seed insects be undertaken once the insects' biology is known.

b) Entomopathogens

31. That a problem analysis be continued of the technical and economic difficulties with using B.t. operationally and that needed research and development be indentified and executed.

32. That more resources be temporarily allocated to making B.t. reliable and cost effective in operational use, particularly against spruce budworm; this short-term control is the nearest of all biological control methods to widespread operational use and is an alternative urgently needed by forest managers.

33. That the potential for improving B.t. potency through strain selection–production methods be given more resources, perhaps through contract research.

34. That much present viral research on sawflies be redirected on ways to improve the infectivity and virulence of spruce budworm viruses.

35. That a watching brief be maintained on tissue culture work emphasizing ways of (a) producing potent virus and (b) reducing the cost of production.

36. That an intensive search be carried out for larger hosts for growing the spruce budworm virus *in vivo*.

37. That petitions for viruses with demonstrated efficacy and reasonable safety data be submitted promptly for registration to Agriculture Canada; this step is particularly important should operational use be anticipated in the near future, such as in B.C., where an outbreak of Douglas-fir tussock moth is now starting.

38. That manpower allocations to fungal pathogens be maintained and directed to more field work aimed at infecting the pest for practical control.

39. That research on protozoan pathogens be concentrated on infecting the pest in the field for practical control. Emphasis should be on synergistic interactions with other control agents.

40. That potential social-environmental problems using fungi or protozoa be clearly identified in planning documentation and methods indicated for dealing with these (evaluation of viruses is already in progress but much too late in the research program according to Health and Welfare Canada). This particularly applies to allergenic properties of fungi.

41. That CFS contract a nematologist in the first instance to look at epizootiology and control possibilities in bark beetle – spruce budworm.

42. That control research of bark beetles with entomopathogens be assessed by PFRC.

c) Fungal metabolites

43. That MFRC review its research using fungal metabolites for tree disease control by assessing the technical feasibility of the method.

iii) Target pests: (essentially regrouping recommendations listed under agents; some are briefly highlighted here but they are not numbered because they are listed previously).

a) Spruce budworm

That long-term methods of control be included in the biological control program. Emphasis should be on (a) predators–parasitoids and (b) manipulating viruses.

b) Bark beetles

That biological control, particularly for long-term protection, be assessed by examining (a) methods for autoinfection with entomopathogens and (b) predator–parasitoid control.

c) Sawflies

That predator–parasitoid work be consolidated and mostly terminated and viral controls submitted for registration.

d) Cone and seed insects

That biological control potential be assessed when the insects' biology is known.

e) That present data on the Douglas-fir tussock moth virus and gypsy moth virus (especially the former) be submitted promptly in petitions for registration. As more emphasis is given to reforestation, nursery and plantation pests should be given special attention.

iv) Possible resource reallocation

In drawing up recommended changes, the important questions are:

Insects - What are the key insects that need controlling and is biological control a useful option?

Control agents - Do any novel (in Canada) concepts of biological control need testing to establish their potential?

Testing location - Where should the work be carried out?

The dominant insect pests are undoubtedly spruce budworms and bark beetles. Reasons are shown earlier why biological control offers an option that is worth pursuing vigorously, including revitalizing our capabilities with predators–parasitoids. Cone and seed insects are pests of increasing importance and biological control options should be explored here, at least to establish the feasibility of the method once the biology of the insects is better understood. With regard to work locations, laboratories closest to the pest problem should undertake the field work. From a scientific viewpoint, it is better to concentrate a large team effort into one or two laboratories rather than divide effort. This concentration would be consistent with the decision taken about 10 years ago, for example, to concentrate some protection research at PFRC by moving personnel from NoFRC. The team effort would be shifted to new problems as opportunities arise (e.g. in intensive forest management).

The most obvious control method that has not been explored at all in Canadian forests is inundation releases of predators–parasitoids despite its apparent success in other countries. This gap in our experience should be filled as soon as possible but it will require considerable resources if the effort is to produce practical conclusions. Two alternative locations seem suited to this work. One is GLFRC–FPMI because of FPMI's sophisticated expertise in insect rearing, although larger facilities would be needed. The target insect could be spruce budworm, provided small isolated pockets can be found (the nearest may be in northern Manitoba according to the 1980 national FIDS report, although Ontario is particularly receptive to testing this approach). The control strategy would be to prevent irruptions of essentially endemic populations including treating epicenters (determined by FIDS) of potential outbreaks. The other location would be PFRC. British Columbia is also particularly interested in biological methods of control and the topography often encourages isolated pockets of insect attack. Furthermore, this approach would provide insect rearing facilities in western Canada (these would not be as sophisticated as FPMI's and would not duplicate present facilities); and if a western center of expertise in predators–parasitoids is to be established, the rearing facilities would be a valuable adjunct.

The following recommendations are thus made in two conditions:

a) The minimum resource reallocation that should be undertaken to strengthen biological control research in CFS is suggested in the Table 10 option and is based on the following observations:

- predator–parasitoid effort too low relative to successes (Table 8).
- fungal effort, although high relative to success (Table 8), should now be concentrated on field work (e.g., in Newfoundland).
- spruce budworm – bark beetle biocontrol not properly explored (Section 10 (ii)(c).
- many remaining predator–parasitoid workers will soon retire (Section 9 (iv)).
- NoFRC, MFRC, NeFRC biocontrol projects negligible (Section 9 (i)).
- no spruce budworm biocontrol research for long-term control (Table 6; Section 10 (ii)(c)) despite control being the key element of the CANUSA agreement and CFS devoting over 100 PY to other spruce budworm research.
- sawfly effort too high relative to present economic losses (Table 6; Section 10 (ii)(c)).
- B.t. work should be given temporary added emphasis to try and provide a reliable and cost effective operational control tool (Section 10 (ii)(b)).
- Nematode control of bark beetles and possibly spruce budworms needs to be assessed (Section 10 (ii)(b)).

Note that to maintain an equitable balance between regions, the predator–parasitoid work has been allocated across the country. Current needs and opportunities are shown in Table 10 for eastern and western regions. The larger perspective is that each regional group functions as a small team testing how biological control can be made to work on selected opportunities, such as the changing pest problems that occur with more intensive forest management. A preferred alternative (and scientifically more efficient way) would be to combine most of the resources into one eastern and one western center. These teams would then address needs as the opportunities arise, and act as centers of expertise.

b) A preferred allocation to include a comprehensive evaluation of inundation releases would include resource re-allocations in Table 10 plus a further 8 PY to cover insect rearing, field releases, monitoring, modelling, and economic studies for inundation releases.

Additional manpower should also be added to the entomopathogen work at FPMI. The whole biotechnology aspect of the program could immediately be strengthened

by adding at least 6 PY to work on biochemical, microbiological, microbial genetic, and fermentation aspects. These additions include needed work on improving B.t. productivity using well-established fermentation techniques (work not being done by industry, particularly not for spruce budworm), but perhaps also genetic engineering to clone the plasmid thought to control endotoxin production in B.t. into *Escherichia coli*, or developing monoclonal antibodies for toxicity assessment. Improved virulence in viruses could also be engineered. In other areas of work, 2 PY could be used for insect genetics to restore this CFS research capability, and 2 PY could be added for mode of action studies, particularly with viruses.

TABLE 1

Biological control activities in each research establishment of the CFS*

Pacific Forest Research Centre	PY	$'000
Fungal entomopathogens - bark beetles	1.9	53.3
Viral entomopathogens - Douglas-fir tussock moth	0.8	20
Predators-parasitoids - larch casebearer - larch sawfly - winter moth	1.0	29.6
Northern Forest Research Centre		
Viral entomopathogens - forest tent caterpillar	0.3	10
Great Lakes Forest Research Centre		
Predators-parasitoids - European pine sawfly - gypsy moth - larch sawfly	4.0	110.7
Dutch elm disease	0.3	10
Laurentian Forest Research Centre		
Bacterial and viral entomopathogens - mainly spruce budworm (B.t.) - Swaine jack pine sawfly (virus)	4.0	141.2
Predators-parasitoids - mainly spruce budworm (red ants) - mountain ash sawfly - gypsy moth	3.4	102.5

TABLE 1 (continued)

Maritimes Forest Research Centre	PY	$ '000
Predators-parasitoids - larch sawfly - European pine shoot moth	0.4	10.0
Entomopathogens - general	0.2	5.0
Tree disease controls - fungal metabolite antagonists	1.1	27.6
Newfoundland Forest Research Centre		
Predators-parasitoids - European pine sawfly - mountain ash sawfly - birch casebearer - birch leafminer	0.8	22.0
Forest Pest Management Institute		
Bacterial entomopathogens - B.t. mainly for spruce budworm	5.0	151.7
Fungal entomopathogens - mainly spruce budworm and hemlock looper	5.0	130.0
Protozoan entomopathogens - mainly spruce budworm	2.0	48.6
Viral entomopathogens - spruce budworm - sawflies - Douglas-fir tussock moth - others occassionally	10.5	246.8
Tissue Culture	3.0	75
Serology	2.0	50
Ultrastructure	1.0	25
Pathogen Survey	1.0	18.5
Petawawa National Forestry Institute		
Fungal entomopathogens - cone and seed insects	0.2	6

* Main source 1981-82 estimates from 1980-81 program plan

TABLE 2

Percentage of CFS biological control funds spent by each establishment and resources allocated per person year (PY)

Establishment	% of total biological control funds	Average $'000 per PY for biological contol*
PFRC	8	27.8
NoFRC	1/2	33
GLFRC	9	28.1
LFRC	19	32.9
MFRC	3	25.1
NeFRC	2	27.5
FPMI	58	25.3
PNFI	1/2	30

* From total PY and total budgets for operations and maintenance and for salaries for biological control at each establishment.

TABLE 3

Current CFS PY for biological control at each establishment

Establishment	Insect control with entomopathogens	Insect control with predators-parasitoids	Disease control
PFRC	2.7	1.0	0
NoFRC	0.3	0	0
GLFRC	0	4.0	0.3
LFRC	4.0	3.4	0
MFRC	0.2	0.4	1.1
NeFRC	0	0.8	0
FPMI	29.5	0	0
PNFI	0.2	0	0
	36.9	9.6	1.4

Source: Estimates for 1981-82 from 1980-81 project statements.

TABLE 4

Current CFS PY for entomopathogen research.

Establishment	Bacteria	Viruses	Fungi	Protozoa	Support*
PFRC	-	0.8	1.9	-	-
NoFRC	-	0.3	-	-	-
GLFRC	-	-	-	-	-
LFRC	3.5	0.5	-	-	-
MFRC	-	-	-	-	0.2
NeFRC	-	-	-	-	-
FPMI	5.0	10.5	5.0	2.0	7
PNFI	- 8.5	- 12.1	0.2 7.1	- 2.0	- 7.2

* Tissue culture, cell biology, ultrastructure research, and pathogen surveys.

TABLE 5

PY allocation to biological control research in the CFS listed by control agent

Agent	% of PY allocation to CFS biological control	% of PY allocation after alloting support*
Bacteria	18	21
Viruses	25	29
Fungi	15	19
Protozoa	4	8
Support*	15	-
Predators-parasitoids	20	20
Tree disease	3	3

* The support activity comprising tissue culture, cell biology, ultrastructure research, and pathogen surveys has been divided between bacteria, viruses, fungi, and protozoa in the last column.

TABLE 6

PY allocations to biological control research in the CFS listed by target pests

	% of biological control manpower
Spruce budworm	57
European pine sawfly	11
Red-headed pine sawfly	7
Gypsy moth	5
Bark beetles	4
Douglas-fir tussock moth	4
Larch sawfly	3
Tree diseases	3
Mountain-ash sawfly	2
Larch casebearer	4
Winter moth	
Forest tent caterpillar	
European pine shoot moth	
Birch casebearer	
Birch leafminer	
Cone and seed insects	
Hemlock looper	
Swaine jack pine sawfly	

TABLE 7

CFS biological control budget as a percentage of the forest protection budget

Establishment	Biological control* budget as % of forest protection budget**	Biological control budget as % of forest protection budget minus FIDS
PFRC	5%	8%
NoFRC	2%	3%
GLFRC	9%	20%
LFRC	4%	8%
MFRC	5%	8%
NeFRC	4%	6%
FPMI	43%	43%
PNFI	1%	1%
All establishments	15%	21%

* Total dollars for biological control from Table 1.

** Total dollars for forest protection obtained from "A concise summary of the Canadian Forestry Service research program" (prepared ca. January 1981), a wrap-up report prepared from 1980-81 program plans. The forest protection program is here labelled as forest fire research, pathology research, FIDS, spruce budworm control research, chemical control of insects, biological control of insects, and general entomological research. Biological control is extracted from all aspects of the program since these labels are not mutually exclusive.

TABLE 8

Relationship between current CFS biological control research by control agents and past control successes

	% of PY in CFS biological control program	Major control successes from CFS research
Bacteria	21	Many lepidopterous forest pests (efficacy erratic)
Viruses	29	European spruce sawfly (plus parasitoids) Douglas-fir tussock moth Redheaded pine sawfly European pine sawfly Swaine jack pine sawfly White - marked tussock moth
Fungi	19	Nil
Protozoa	8	Nil
Predators-parasitoids	20	European spruce sawfly (plus virus) Larch sawfly Introduced pine sawfly Satin moth Larch casebearer Winter moth Mountain - ash sawfly European pine shoot moth
Tree diseases	3	Nil

TABLE 9

Relative probability of future control successes

Agent	Technical success*	Economic success	Social acceptance
Predators-parasitoids	good	situation-specific**	good
Bacteria	good	good	average
Viruses	good	average	average
Fungi	poor	average	average
Protozoa	poor	average	average

* Rating is based on past success record (Table 8).

** Variable depending on whether inundation releases, inoculative releases, or moderate augmentation is planned.

TABLE 10

Proposed changes in PY allocations to biological control programs within the CFS

Location	PY Change	Present or past control need	Biological control opportunity*
PFRC	+2	bark beetles	predators-parasitoids entomopathogens
NoFRC	+1	bark beetles	pedators-parasitoids
GLFRC	+3 -2	spruce budworm (sawflies)	predators-parasitoids (predators-parasitoids)
LFRC	+2	spruce budworm	B.t.
MFRC	+4	spruce budworm	predators-parasitoids
NeFRC	+1 +1	spruce budworm spruce budworm	predators-parasitoids entomopathogens
FPMI	+2 +2 -2	spruce budworm spruce budworm (sawflies)	B.t. virus (virus)
PNFI	0		

* The opportunity is listed only by biological control agent irrespective of whether the particular need is for taxonomists, modellers, parasitologists, or others.

BIBLIOGRAPHY

Allen, G. E., C. M. Ignoffo, and R. P. Jaques. 1978. Microbial control of insect pests: future strategies in pest management systems. Natl. Sci. Found., U.S. Dep. Agric., Univ. Fla. workshop.

Anagnostakis, S. L. 1981. Biological control of chestnut blight. Science 215:466.

Anon. 1962. Biological control of spruce budworm. Commonw. Inst. Biol. Control Tech. Comm. No. 2:75.

Anon. 1975. Pest control: An assessment of present and alternative technologies. Natl. Acad. Sci., Washington, DC.

Anon. 1977a. New innovative pesticides: An evaluation of incentives and disincentives for commercial development by industry. Stanford Res. Inst., Menlo Park, CA.

Anon. 1977b. Department of Environment Policy Statement on Aerial Spray Programs for Forest Protection, 14 Dec., 1977.

Anon. 1978. Biological agents for pest control: Status and prospects. Report of a special study team. U.S. Dep. Agric., Washington, DC.

Anon. 1980a. Proceedings of workshop on insect pest management with microbial agents: Recent achievements, deficiencies, and innovations. Boyce Thompson Inst., Ithaca, NY.

Anon. 1980b. Operational trials against the Douglas-fir tussock moth with chemical and biological insecticides 1975-1976. Can. For. Serv. Inf. Rep. BC-X-20.

Anon. 1981a. Feasibility study for a biological control production facility. Schultz Int. Ltd., Vancouver, B.C.

Anon. 1981b. Position paper on mountain pine beetle problems with special reference to the Rocky Mountain parks region. Can. For. Serv., Pac. Forest Res. Cent.

Anon. 1981c. Minutes of interagency meeting on the mountain pine beetle. Vancouver, B.C. 21 April.

Anon. 1981d. Biotechnology: A development plan for Canada. Report of Task Force on Technology. Minister of Supply and Services, Canada. Cat. ST 31-9/1981 E

Baker, K. F. 1980. Microbial antagonism - the potential for biological control. Pages 327-348 *in* D. C. Ellwood, J. N. Hedger, M. J. Latham, J. H. Slater, and J. M. Lynch, editors. Contemporary microbial ecology. Academic Press, New York, NY.

Baker, K. F., and R. J. Cook. 1974. Biological control of plant pathogens. Freeman, San Francisco, CA.

Baskerville, R. 1976. Report of the task-force for evaluation of budworm control alternatives. Prepared for the cabinet committee on economic development, Province of New Brunswick, Fredericton, N.B.

Bennett, F. D. 1980. Advances in insect pest control. II. Arthropods for biological control of forest pests and weeds. Eleventh Commonw. For. Conf., Trinidad and Tobago.

Berryman, A. A., and L. Safranyik, editors. 1980. Proceedings Second IUFRO Conf. on dispersal of forest insects, evaluation, theory, and management implications. Can. For. Serv. and U.S. Dep. Agric.

Bustillo, A. E., and A. T. Drooz. 1977. Cooperative establishment of a Virginia (U.S.A.) strain of *Telenomus alsophilae* on *Oxydia trychiata* in Colombia. J. Econ. Entomol. 70:767.

Cameron, M. D., and T. R. Renault. 1973. Recent introductions from Japan for biological control of spruce budworm. Marit. Forest Res. Cent. Intern. Rep. M-75.

Carrow, J. R. 1981. Insect protection and management research. Submission to the Industrial Assessment of Silviculture Research, Pulp and Paper Res. Inst. of Can., Pointe Claire, Que.

De Bach, P. 1964. Successes, trends, and future possibilities. Page 673 *in* P. De Bach editor. Biological control of insect pests and weeds. Chapman and Hall, London, England.

De Bach, P. 1974. Biological control by natural enemies. Cambridge, London.

Harper, J. D. 1974. Forest insect control with *Bacillus thuringiensis*. Auburn University, Auburn, AL.

Harris, P., and R. Cranston. 1979. An economic evaluation of control methods for diffuse and spotted knapweed in western Canada. Can. J. Plant Sci. 59: 375.

Huffaker, C. B., and P. S. Messenger. 1976. Theory and practice of biological control. Academic Press, New York, NY.

Huffaker, C. B., editor. 1980. New technology of pest control. John Wiley and Sons Inc., New York, NY.

McNamee, P. J., J. M. McLeod, and C. S. Holling. 1981. The structure and behavior of defoliating insect/forest systems. Inst. Resour. Ecol., Univ. B.C., Vancouver.

Marschall, K. J. 1980. Rhinoceros beetle project. Proc. workshop on insect pest management with microbial agents. Boyce Thompson Inst., Ithaca, NY.

Marsden, J. S., G. E. Martin, D. J. Parham, T. J. Ridsill Smith, and B. G. Johnston. 1980. Returns on Australian agricultural research: The joint IAC -CSIRO benefit cost study of the CSIRO Division of Entomology. Commonwealth Scientific and Industrial Research Organization, Canberra, Australia.

Miller, C. A. 1963. Parasites and the spruce budworm. Page 228 *in* R.F. Morris, editor. The dynamics of epidemic spruce budworm populations. Mem. Entomol. Soc. Can. 31.

Miller, C. A., and I. W. Varty. 1975. Biological methods of spruce budworm control. For. Chron. 51:150.

Milligan, R. H. 1978. Control of pine bark beetle. For. Timber Inst., New Zealand, 29, 8 p.

Munroe, G. 1971. Status and potential of biological control in Canada. Commonw. Inst. Biol. Control Tech. Comm. No. 4:213-255.

Norton, G. A., and C. S. Holling, editors. 1976. Proc. Conference on pest management. Int. Inst. Appl. Syst. Anal., Laxenburg, Austria.

Ordish, G. 1976. A short history of pests and control. Scribner's, New York, NY.

Pimentel, D. 1963. Introducing parasites and predators to control native pests. Can. Entomol. 95:785.

Ridgeway, R. L., and S. B. Vinson, editors. 1977. Biological control by augmentation of natural enemies. Plenum Press, New York, NY.

Rishbeth, J. 1971. Biological control for root diseases of trees. *In* V. J. Nordin, editor. Biological control of forest diseases. Fifteenth IUFRO Congr., Gainesville, FL.

Schacht, A. T. 1981. Record of decision. 1981–85 Cooperative Spruce Budworm Management Program for Maine, Spruce Budworm Management Program USDA-FS-NA-81-01.

Simmonds, F. J. 1967. The economics of biological control. J. Royal Soc. Arts 115: 880.

Smith, R. B., and A. Funk. 1980. Assessing *Nectria macrospora* as a biological control agent for hemlock dwarf mistletoe. Bi-mon. Res. Notes 36:11.

Stark, R. W., and D. L. Dahlsten. 1970. Studies on the population dynamics of the western pine beetle. Univ. Calif., Div. Agric. Sci.

Strobels, G. 1981. Use of *Pseudomonas syringae* to control Dutch elm disease. Proc. Symp. and Workshop on Dutch elm disease, Winnipeg, Man. Dep. Nat. Resour.

Thatcher, R. C., J. L. Searcy, J. M. Coster, and G. D. Hertel, editors. 1980. The southern pine beetle. USDA-FS Tech. Bull. 1631.

Van den Bosch, R. 1975. Biological control of insects by predators and parasites. Env. Lett. 8:5.

Van den Bosch, R., and P.S. Messenger. 1973. Biological control. Intertext Educational Publishers, New York, NY.

Wellenstein, G., editor. 1954. Die grosse Borkenkaferkalamitat in Sudwestdeutschland 1944-1951. Gesamtherstellung, Ulm.

Wicker, F. 1978. Biological control of tree diseases. Proc. 26th Annu. West. Int. Forest Dis. Workshop, Tuscon, AZ, Oct. 24-28.